NASA
CR
3304
c.1

LOAN COPY: RETURN TO
AFWL TECHNICAL LIBRARY
KIRTLAND AFB, N.M.

0062074

TECH LIBRARY KAFB, NM

NASA Contractor Report 3304

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project -

Initial Act Configuration Design Study, Summary Report

Staff of Boeing Commercial Airplane Company

CONTRACTS NAS1-14742
and NAS1-15325

OCTOBER 1980

FOR EARLY DOMESTIC DISSEMINATION

Because of its significant early commercial potential, this information, which has been developed under a U.S. Government program, is being disseminated within the United States in advance of general publication. This information may be duplicated and used by the recipient with the express limitation that it not be published. Release of this information to other domestic parties by the recipient shall be made subject to these limitations.

Foreign release may be made only with prior NASA approval and appropriate export licenses. This legend shall be marked on any reproduction of this information in whole or in part.

Review for general release July 30, 1982.

NASA

TECH LIBRARY KAFB, NM

0062074

NASA Contractor Report 3304

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project -

Initial Act Configuration Design Study, Summary Report

Staff of Boeing Commercial Airplane Company
The Boeing Commercial Airplane Company
Seattle, Washington

Prepared for
Langley Research Center
under Contracts NAS1-14742 and NAS1-15325

NASA
National Aeronautics
and Space Administration

Scientific and Technical Information Branch

1980

FOREWORD

This document constitutes the summary report of the Initial ACT Configuration Design Task, the first configuration development work accomplished under the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project. The IAAC Project is focused on determining the effect of incorporating active controls technology (ACT) early in the design of a commercial transport airplane. This project is one element of the NASA Energy Efficient Transport Program, with the common objective of improving the energy efficiency of commercial transports.

This specific task was begun under Contract NAS1-14742 and was completed under Contract NAS1-15325. NASA technical monitors for this task were D. B. Middleton and R. V. Hood of the Energy Efficient Transport Program office at Langley Research Center.

The work was accomplished within the Preliminary Design Department of the Vice President-Engineering organization of the Boeing Commercial Airplane Company. Key contractor personnel who contributed to this task were:

G. W. Hanks	Program Manager
H. A. Shomber	IAAC Project Manager
H. A. Dethman	Design Integration
L. B. Gratzer	Technology Integration
C. C. Flora	Task Manager (Initial ACT)
R. L. Sullivan	Aerodynamic Technology
G. E. Seidel	Configurations
A. Maeshiro	Flight Control Technology
C. E. Roth	Flight Control Technology
E. Heineman	Structures Design
J. F. Bueno-Varela	Structures Technology
M. T. McIntosh	Structures Technology
M. J. Omoth	Systems Technology
J. D. Brown	Weight Technology

During this study, principal measurements and calculations were in customary units and were converted to Standard International units for this document.

CONTENTS

	Page
SUMMARY	1
INTRODUCTION	3
CONVENTIONAL BASELINE CONFIGURATION	5
INITIAL ACT CONFIGURATION DESCRIPTION	7
DESIGN REQUIREMENTS AND OBJECTIVES	9
ACTIVE CONTROL FUNCTIONS	11
WING PLACEMENT AND LANDING GEAR DESIGN	13
STRUCTURAL ANALYSIS	15
INITIAL ACT CONFIGURATION CONTROL SURFACES	17
ACT SYSTEM SENSORS	19
ACTIVE CONTROL SYSTEM MECHANIZATION	21
RELIABILITY AND MAINTAINABILITY	23
FUNCTIONAL WEIGHT ASSESSMENT	25
CENTER-OF-GRAVITY MANAGEMENT	27
AERODYNAMICS	29
PERFORMANCE	31
RETURN ON INVESTMENT	33
CONCLUSIONS	35
REFERENCES	37

SUMMARY

This report summarizes the first ACT airplane configuration task in a project entitled "Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport." The performance and economic benefits of a constrained application of active controls technology (ACT) were identified, and the approach to airplane design for subsequent steps leading to the development of a less-constrained Final ACT Configuration was established. The Conventional Baseline Configuration, a state-of-the-art modern transport selected and defined in a previous task, was used as a yardstick against which the active controls configurations were measured to determine whether the performance and economic changes resulting from including ACT were of sufficient magnitude to merit proceeding with the project. Reduced mission fuel resulting from incorporating ACT into these airplane configurations was a key element in the evaluation.

The levels of technology incorporated in the Conventional Baseline Configuration were held constant, except for the addition of ACT.

The Initial ACT Configuration was developed with the same wing planform as the Conventional Baseline, but with the wing moved forward 1.68m (66 in) to produce a further aft center-of-gravity range. Wing trailing-edge surfaces and surface controls were reconfigured for load alleviation and structural stabilization. It was assumed that all required ACT functions could be made available with a mechanization appropriate to commercial airline service.

Incorporating a pitch-augmented stability system made possible an approximately 10% aft shift in cruise center of gravity and a 45% reduction in horizontal tail size. Even though extra fuel tanks were added to the outboard wing to preclude flutter, the overall wing structure became lighter because of its dependence upon wing-load alleviation functions. The net effect of these changes was a 930-kg (2050-lb) reduction in airplane operating empty weight (OEW). The Initial ACT and Conventional Baseline Configurations are compared in Figure 1.

The Initial ACT Configuration was not resized to the Baseline mission. Consequently, there was a 13% increase in range, at the same takeoff gross weight and payload as the Conventional Baseline Configuration, due to a 3.6% improvement in cruise aerodynamic efficiency and the reduced OEW. Adjusted to the 3590-km (1938-nmi) Baseline mission range, this amounts to approximately a 6% reduction in block fuel, and a 15.7% incremental return on investment (ΔROI); i.e., the incremental capital costs (based on factored cost data) for design, development, and installation of the equipment and configuration differences between the Initial ACT and Baseline Configurations. This 15.7% ROI corresponds to a \$0.1057/ℓ (\$0.40/gal) fuel cost, in 1978 dollars. Much larger ROI may be expected if historical fuel inflation rates continue. Further details of the Initial ACT Configuration physical characteristics, performance, and economics are contained in the body of this report and in the Initial ACT Configuration Design Study Final Report, Reference 1.

The results of the Initial ACT Configuration Design Task clearly indicated that the IAAC Project should proceed in order to determine what further benefits may be achieved through wing planform changes and advanced technology systems.

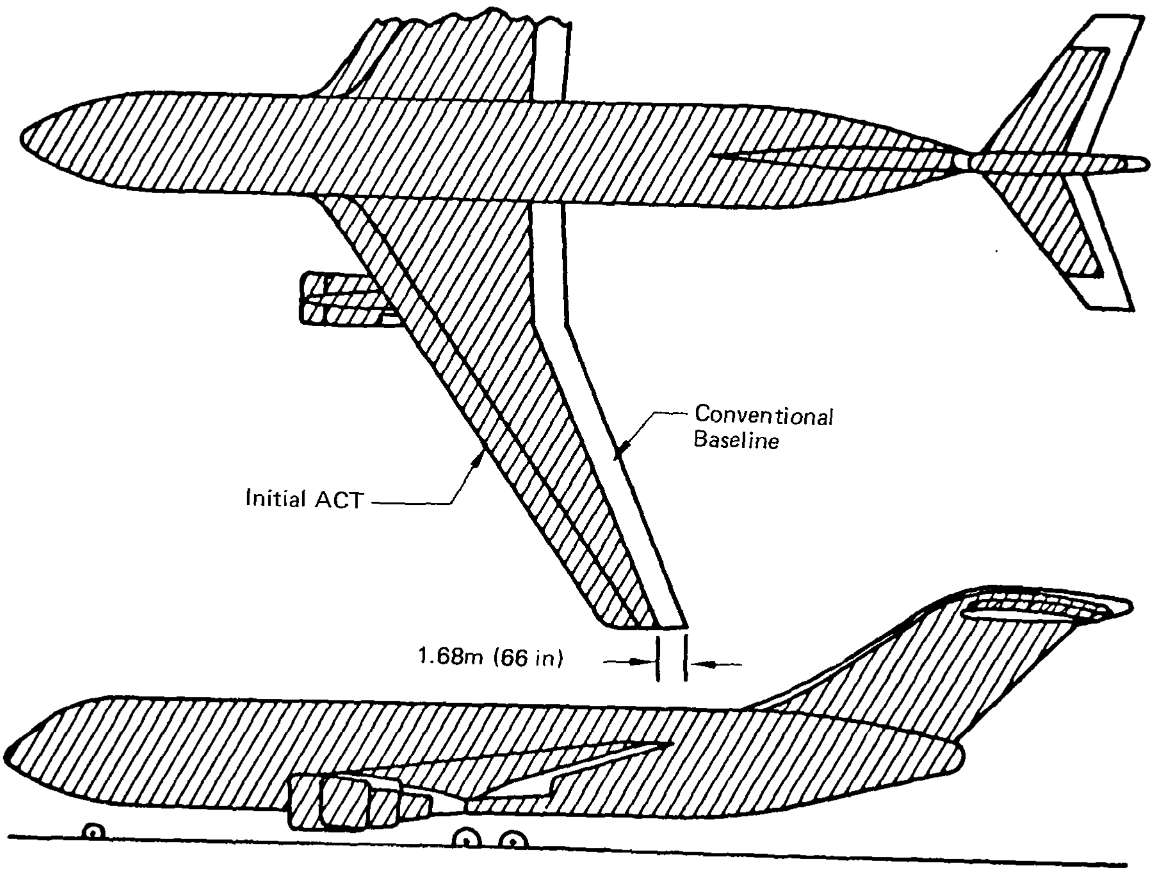


Figure 1. Initial ACT and Conventional Baseline Configuration Comparison

INTRODUCTION

Although active controls have been used in several past commercial transports, these applications are either very limited in scope or have been added after the airplane was in production. Typically, these additions were made either to overcome an unanticipated difficulty or to add capability to the airplane. A considerable body of evidence suggests that the greatest benefit from application of active controls technology to a transport airplane will result from incorporating ACT early in the design process. Although this evidence provides a strong indicator of benefit, its credibility is lacking because there have been no significant applications of ACT to date.

The principal objective of the IAAC Project was therefore to assess the benefits associated with design of a commercial ACT transport. During development of this benefit assessment, certain technical risk areas became clear. This led to the second objective of the IAAC Project, which was to identify technical risk areas and to recommend appropriate test and development programs. The final objective was to pursue their resolution to the maximum possible extent within project resource limitations.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

IAAC PROJECT

The IAAC Project was made up of three major elements, as shown in Figure 2 (ref 2). The first, Configuration/ACT System Design and Evaluation, addressed the design of an ACT transport in sufficient detail to clearly identify the performance and economic benefits associated with the use of ACT. This airplane design incorporated all beneficial ACT systems with current technology implementation assumed. This yielded a performance and economic assessment that incorporated little technical risk from a systems viewpoint and thus did not compromise the credibility of the overall ACT evaluation.

In parallel, work was initiated on the second major element, Advanced Technology ACT Control System, to identify potential improvements through use of optimal control law synthesis techniques and/or advanced technology components for the implementation of ACT systems.

Following the benefits assessment, the final major element, Test and Evaluation, began work designed to reduce selected real or perceived technical risks associated with implementation of ACT.

IAAC Ground Rules

A modern Conventional Baseline Configuration, without any significant application of ACT, was required to determine the benefits of ACT. This reference airplane configuration also established the design mission for the ACT configurations. The technology of the ACT airplanes designed under this project was fixed at the level established by the Baseline Configuration, except for ACT.

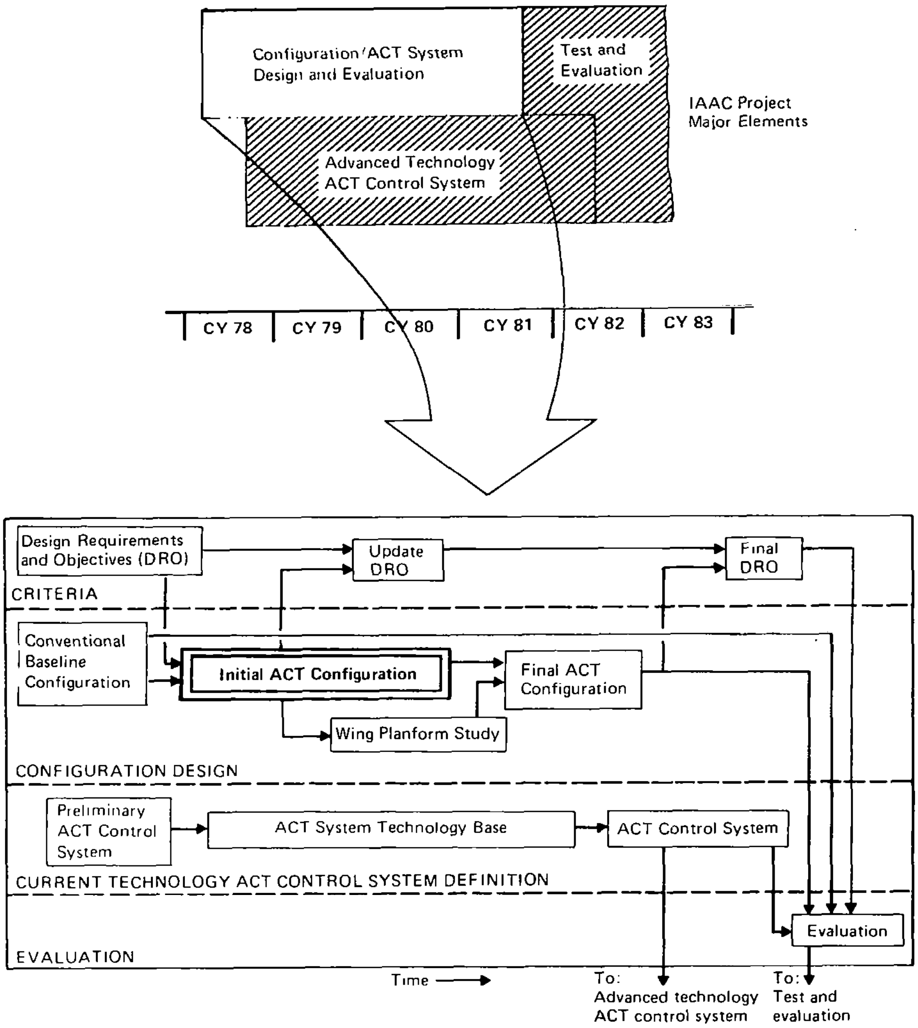


Figure 2. Relationship of Initial ACT Configuration Design Task to the Overall IAAC Project

The airplane configuration design work proceeded under the assumption that any beneficial ACT function could be implemented with appropriate reliability and availability. The Current Technology ACT Control System Definition Task proceeded, in parallel, to determine a suitable low-technical-risk implementation.

Initial ACT Configuration Design Task

The first configuration development step of the IAAC Project, the Initial ACT Configuration Design Task, is the subject of this summary report. Its objectives were to identify the performance and economic benefits of ACT as applied to the Conventional Baseline and to establish the design approach for the subsequent steps in the development of the Final ACT Configuration. Figure 2 shows the relationship of the Initial ACT Configuration Design Task to the Configuration/ACT System Design and Evaluation element of the total program. This report summarizes the work accomplished, and Reference 1 contains more detail of this work.

CONVENTIONAL BASELINE CONFIGURATION

Domestic trunk operations use about 28.5 billion liters (7.5 billion gallons) of fuel annually. One airplane-type (727) fleet uses one-half as much fuel as all other types of airplanes in domestic trunk operation combined; e.g., approximately 9.5 billion liters (2.5 billion gallons) annually (ref 3). The greatest potential leverage of this study on domestic trunk air carrier fuel use, therefore, resulted from design of an ACT airplane that could perform the mission of that fleet. The Conventional Baseline Configuration selected for this study is a 197-passenger (plus cargo), nominal 3590-km (1938-nmi) design range airplane and is projected to satisfy the selected mission, considering market demands for the post-1985 period.

This selection allowed Boeing to apply a considerable amount of available analytical and test data derived during earlier preliminary design efforts. The existing data base was reviewed and additional analysis was conducted as necessary to complete the technical descriptions. The resulting Baseline Configuration, shown in Figure 3, uses a double lobe, but nearly circular body, with seven-abreast seating. It has an 8.71-aspect-ratio, 31.5-deg swept wing; a T-tail empennage; and two wing-mounted CF6-6D2 engines. The lower lobe has volume for 22 LD-2 or 11 LD-3 containers, plus bulk cargo. Operationally, passenger and cargo loading, servicing provisions, taxi and takeoff speeds, and field length characteristics are all compatible with accepted airline and regulatory provisions.

The Baseline Configuration uses conventional aluminum structure except for advanced aluminum alloys and a limited amount of graphite-epoxy secondary structure. Modern systems are used, including advanced guidance, navigation, and controls, that emphasize application of digital electronics and advanced displays.

Further characteristics and performance details are contained in the Conventional Baseline Configuration Task Final Report, Reference 4.

Configuration	
Passengers	197 mixed class, 207 all tourist
Containers	22 LD-2, or 11 LD-3
Engines	(2) CF6-6D2
Design mission	
Cruise Mach	0.8
Range	3590 km (1938 nmi)
Takeoff field length	2210m (7250 ft)
Approach speed	70 m/s (136 kn)
Noise	FAR 36, Stage 3
Flying qualities	Current commercial transport practice
Airplane technology	Current commercial transport practice (aerodynamics, structural, propulsion, etc.)

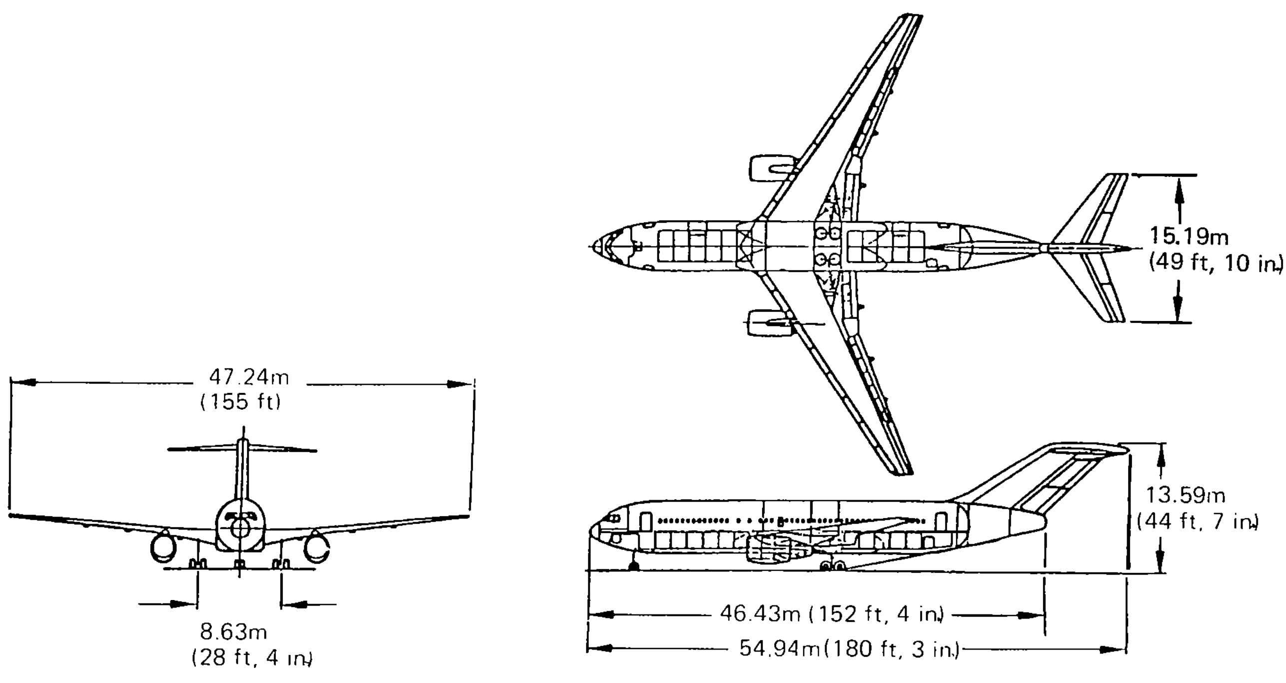


Figure 3. Baseline Configuration General Arrangement

INITIAL ACT CONFIGURATION DESCRIPTION

Throughout the Configuration/ACT System Design and Evaluation Task, the technology level for structures, propulsion, and aerodynamics was held constant at the level established by the Conventional Baseline Configuration so that only benefits from ACT applications could be assessed.

Development of the Initial ACT Configuration was constrained to meet the specific objectives of this task in the most efficient manner. One very important constraint was the maintenance of wing planform and area in order to understand the impact of ACT on an airplane designed to the same aerodynamic performance level as the Baseline. The Baseline Configuration takeoff gross weight, propulsion system, and empennage planform were also held fixed to enable the ACT performance increment to be assessed with significantly less resources than would otherwise be required. The Initial ACT Configuration was not resized for constant payload/range. Therefore, reductions in block fuel and range increase at constant payload were taken as measures of the performance improvement. Major configuration options were maintained to ensure a flexible and economically attractive commercial transport.

The principal dimensions and general arrangement of the Initial ACT Configuration resulting from the study are shown in Figure 4. It is a twin-engine, low-wing, land-based commercial transport airplane with a design range of approximately 4061 km (2193 nmi), a payload of 197 passengers (in mixed-class accommodations), and 22 LD-2 containers. Two General Electric CF6-6D2 engines, in wing pylon-mounted nacelles, power the airplane. Structural materials and design practice are conventional, using aluminum alloy for the primary structure with a limited amount of graphite-epoxy secondary structure, and other materials such as high-strength steel for landing gear components.

Configuration	
Passengers	197 mixed class, 207 all tourist
Containers	22 LD-2, or 11 LD-3
Engines	(2) CF6-6D2
Design mission	
Cruise mach	0.8
Range	4061 km (2193 nmi)
Takeoff field length	2118m (6950 ft)
Approach speed	68.6 m/s (133.4 kn)
Noise	FAR 36, Stage 3
Flying qualities	Current commercial transport practice
Airplane technology	Current commercial transport practice (aerodynamics, structural, propulsion, etc.)

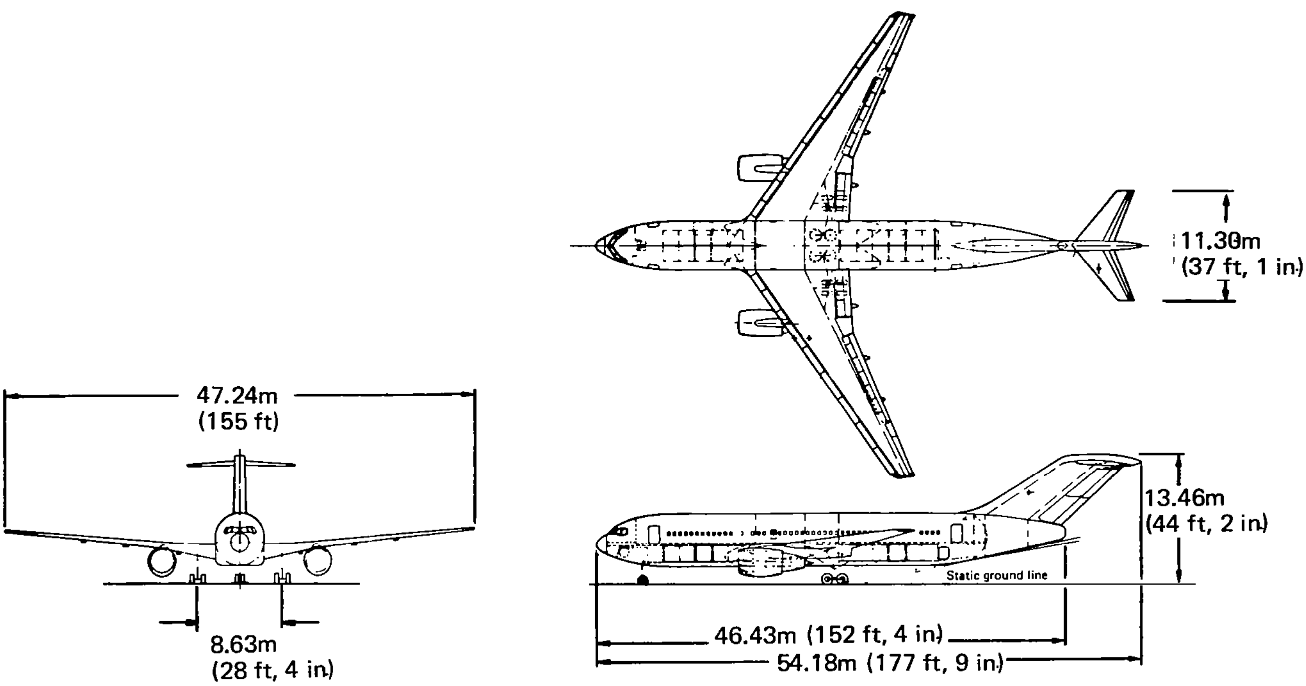


Figure 4. Initial ACT Configuration General Arrangement

DESIGN REQUIREMENTS AND OBJECTIVES

The overall strategy of the IAAC Project was to identify the benefits due to ACT functions by carefully including only changes due to active controls, while retaining other characteristics of the Conventional Baseline Configuration. For instance, the ACT configurations were to be no quieter than the Conventional Baseline Configuration, if such improved noise characteristics would result in a performance penalty. The foundation for achieving this goal of the study was identification of the design requirements and objectives (DRO) for the Baseline, development of an understanding of what aspects of that DRO had to be changed to allow incorporation of active controls, and selection of the DRO for the ACT airplanes.

Development of the DRO for the Initial ACT Configuration has shown that most of the conventional airplane requirements will apply with little or no modifications to an ACT airplane. One exception is flying qualities criteria. A conventional airplane will typically exhibit safe, if not satisfactory, characteristics following the failure or functional loss of certain augmentation systems or automatic controls. In contrast, an ACT airplane designed to be dependent upon augmentation will experience degraded, in some areas unsafe, characteristics if that augmentation ever totally fails. Therefore it is essential to develop and validate practical augmentation, including software, that meets the stringent reliability requirements of commercial transports in order for such airplanes to be realized.

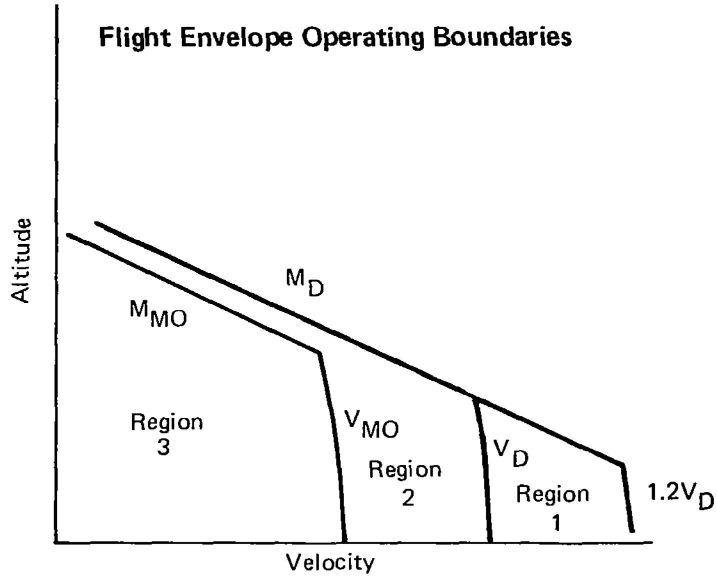
The other significant area of departure from the Conventional Baseline DRO was the specification of flutter criteria. As summarized in Figure 5, current flutter criteria for conventional airplanes require that the airplane shall be shown to be flutter free:

- By analysis and model tests, up to a speed 20% beyond the design dive speed; i.e., $1.2V_D$ (region 1 in fig. 5)
- By flight test, to the design dive speed; i.e., V_D (region 2 in fig. 5)

The IAAC criteria for an airplane that uses a flutter-mode control system are shown in the right-hand column in Figure 5. These criteria require that the airplane shall be shown to be flutter free:

- By flight test, with the flutter-mode control (FMC) inoperative, throughout the normal operating envelope up to the maximum operating speed; i.e., V_{MO}/M_{MO} (region 3 in fig. 5)
- By flight test, with the FMC operational, up to the design dive speed; i.e., V_D (region 2 in fig. 5)
- By analysis and model test, with the FMC inoperative, up to the design dive speed; i.e., V_D (region 2 in fig. 5)
- By analysis and model test, with the FMC operational, up to a speed 20% beyond the design dive speed; i.e., $1.2V_D$ (region 1 in fig. 5)

A more detailed discussion of the ACT aspects of the design requirements and objectives used in the Initial ACT Configuration Design Task is contained in Appendix A of Reference 1.



Criteria

Airplane shall be free from flutter in accordance with:

Region	Current criteria for conventional airplanes	Criteria for airplanes with flutter mode control
1	By analysis and model test to $1.2V_D$	By analysis and model test to $1.2V_D$ with FMC on
2	By flight test to V_D	By analysis and model test to V_D with FMC off By flight test to V_D with FMC on
3		By flight test to V_{MO} with FMC off

Figure 5. Flutter Criteria

ACTIVE CONTROL FUNCTIONS

Active control functions were selected for the Initial ACT Configuration based on a preliminary assessment of the expected benefit in airplane weight or drag reduction. No formal quantitative risk versus benefit evaluation was made prior to selecting the following functions:

- Pitch-Augmented Stability (PAS)—The PAS function augments the airplane longitudinal stability to provide acceptable flying qualities. Long-period (phugoid) and short-period (static stability) augmentation are included.

- Lateral/Directional-Augmented Stability (LAS)—The LAS function is a conventional yaw-damper identical to that of the Baseline Configuration.

- Angle-of-Attack Limiter (AAL)—The AAL function prevents the airplane from exceeding a limiting angle of attack. By limiting angle of attack to a small margin beyond that for maximum lift, it is possible to reduce the horizontal tail size required to provide nosedown control margin for stall recovery.

- Wing-Load Alleviation (WLA)—The WLA function has two submodes:

    - Maneuver-Load Control (MLC)—MLC reduces the wing vertical bending moment in longitudinal maneuvers by deflecting the outboard ailerons to redistribute the wing loads.

    - Gust-Load Alleviation (GLA)—GLA reduces the wing loads due to atmospheric disturbances by deflecting outboard ailerons to reduce and redistribute the induced loads.

- Flutter-Mode Control (FMC)—The FMC function stabilizes the wing critical flutter mode from V_D to $1.2V_D$ by sensing wing normal acceleration and commanding deflection of the inboard segment of the outboard aileron.

Use of ACT to meet longitudinal stability requirements allowed the horizontal tail to be sized by only controllability requirements, as shown in Figure 6.

The aft center-of-gravity controllability limit was set by the requirement to develop stall recovery pitching moments at the maximum angle of attack achievable. Without control system provisions to limit the maximum angle of attack, controllability becomes critical for a T-tail configuration at very large post-stall angles of attack. By providing angle-of-attack limiting, the required recovery pitching moment could be reduced to the level necessary for recovery from an angle of attack only a small increment above the angle of attack required to develop maximum lift. Thus the tail size was significantly smaller for any particular aft center of gravity for the airplane with an alpha-limiter. As shown in Figure 6, the limiting aft center-of-gravity condition changed from deep stall recovery to normal stall recovery with incorporation of an alpha-limiting system (denoted by arrow).

Typically, forward center-of-gravity limits are set by either landing approach or takeoff rotation. The takeoff rotation requirement for mistrim was reduced by providing a "green band" that limited the range of acceptable trim settings and a

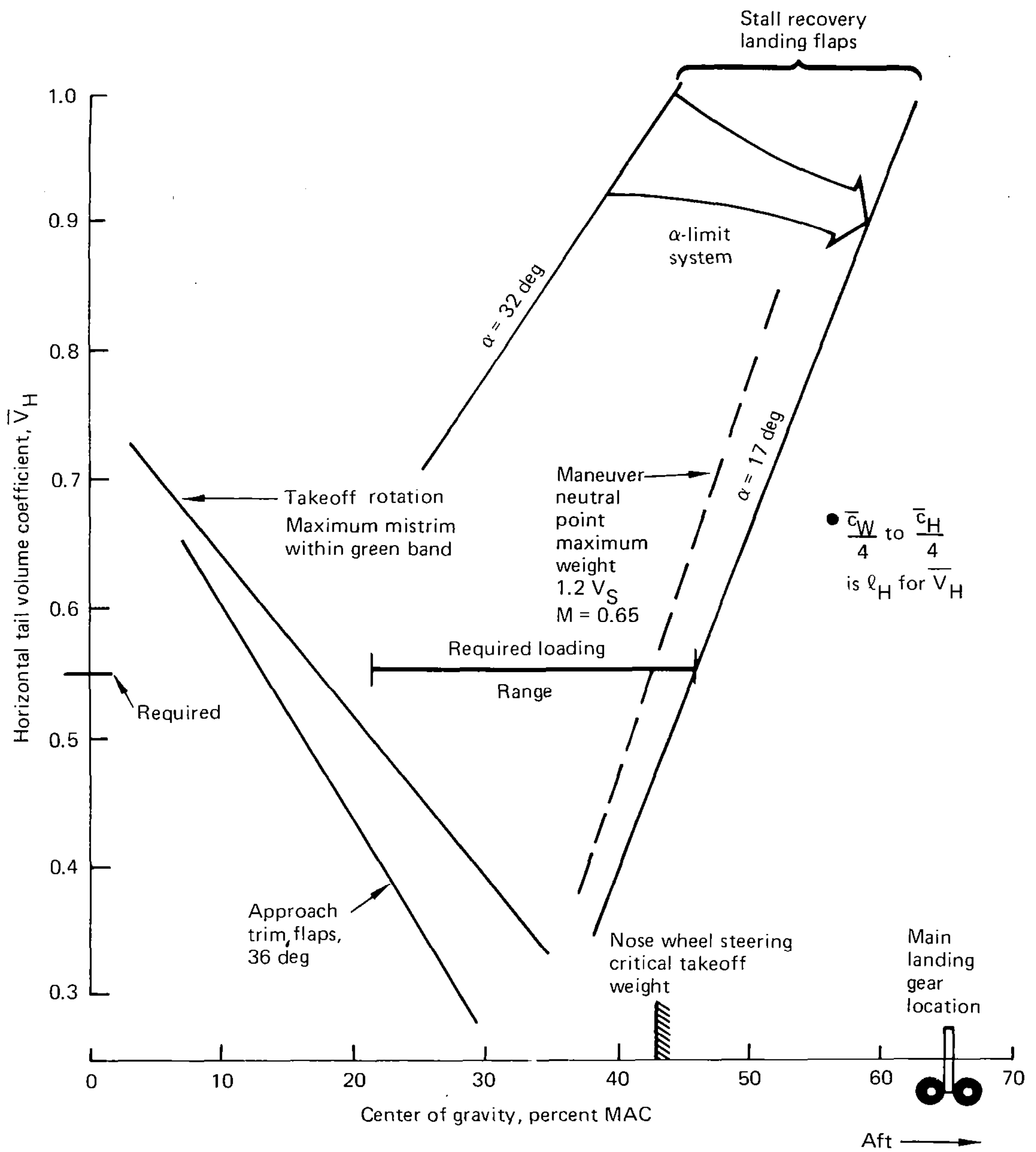


Figure 6. Horizontal Tail Size Requirements

warning system to preclude takeoff with trim set outside this range. Consequently the Initial ACT Configuration tail size was not critical at the forward center-of-gravity limit.

The vertical tail size was also set by control requirements; i.e., engine-out control, with a yaw damper included as in the Conventional Baseline Configuration to improve the lateral/directional dynamics.

WING PLACEMENT AND LANDING GEAR DESIGN

A clear assessment of the benefit of ACT required that the ACT configurations be equivalent to the Conventional Baseline Configuration in all important aspects. For example, the ACT configurations have the same cargo container capacity as the Conventional Baseline Configuration. This in turn required that the wing movement necessary to accomplish a more aft center-of-gravity location had to occur in increments of lower deck cargo containers. In other words, the wing had to be moved in approximately 1.68m (66 in) steps, which is the space required for one row of containers. Consequently, the aft end of the required loading range coincided with the aft controllability limit, but was not critical at the forward limit, as shown in Figure 6.

Twin-engine airplanes typically require a higher total installed thrust than airplanes with a greater number of engines. To provide adequate nose-gear steering, twin-engine airplanes with the thrust line below the center of gravity (typical wing-mounted engines) require a sufficient distance between the aft center of gravity and the effective center of rotation of the landing gear with the airplane on the ground to maintain nose-gear loads for steering following brake release at takeoff thrust. This requirement caused the main gear installation to be one of the major design problems of this configuration. Retention of the wing planform (Initial ACT Configuration ground rule) was inconsistent with the desired aft shift of the center-of-gravity range and retention of the Baseline Configuration main landing gear. It was necessary to move the effective center of rotation aft with respect to the wing. By incorporating a side-braced main landing gear concept with a dog-leg-canted strut (fig. 7), the required center-of-gravity and landing gear relationships were established.

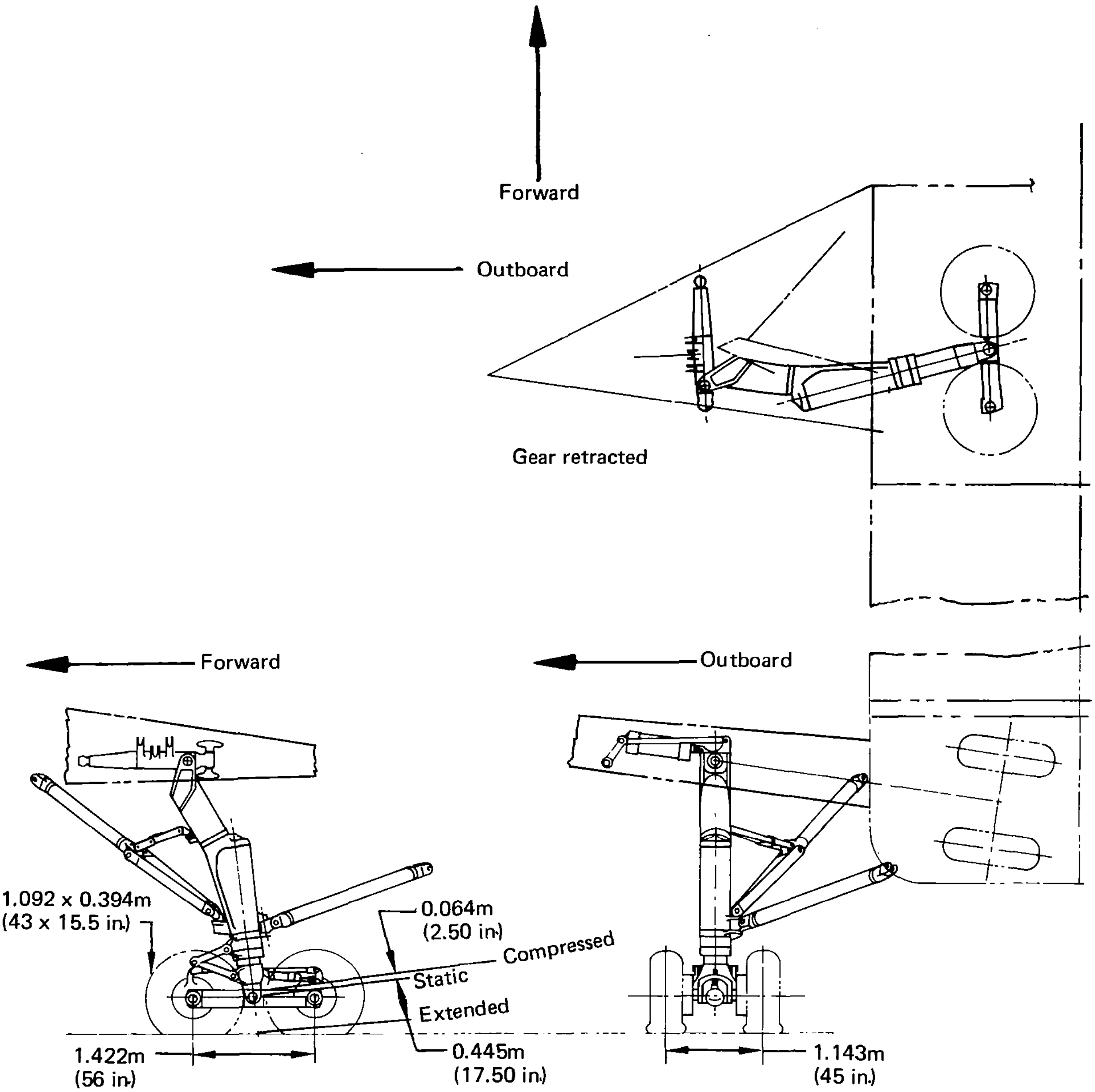


Figure 7. Main Landing Gear

STRUCTURAL ANALYSIS

The wing-box theoretical structural material that satisfied all basic structural requirements, with operating ACT systems, is presented in Figure 8. This material requirement is shown in the figure in terms of the cross-sectional area perpendicular to the load reference axis.

The wing-load alleviation (WLA) system is effective in reducing the structural material requirements in the upper and lower surfaces, for maneuver and gust conditions. However, its effect on spar web material is negligible. The resulting lower inboard wing surface was fatigue critical without a fatigue reduction system. Consequently, to take maximum advantage of the weight reduction from the WLA system, it was necessary to include the fatigue reduction properties of the WLA system, which reduced alternating stresses from continuous turbulence and maneuvers. The outboard wing upper and lower surfaces were designed by continuous turbulence criteria (gusts). The active controls investigated were found to have a limited effect in reducing these loads.

The requirement that the airplane be flutter free without FMC to V_D was satisfied by increasing the spar web thicknesses to the thinner of the local skin gages and incorporating an outboard reserve fuel tank. Flutter stability between V_D and $1.2V_D$ was achieved using a flutter-mode control system. An alternative passive fix would have required increases in the wing-box skins in the inboard wing section ($\eta = 0.15$ to 0.35), resulting in a significant weight increase. Maximum benefit was realized by incorporating wing-load alleviation and flutter-mode control active control systems.

The basic objectives of the preliminary horizontal tail structural analysis were to calculate aeroelastic effects on elevator and tail aerodynamic derivatives and to assess the effects of tail load changes on aft body strength and stiffness. Maximum tail loads were used for structural sizing and tail stiffness calculations.

The horizontal tail design loads for the Initial ACT Configuration with relaxed static stability were lower than the tail design loads for the Conventional Baseline Configuration. This was primarily due to an increase in tail arm resulting from the 1.68m (66-in) forward wing shift in the Initial ACT Configuration and to the change in center-of-gravity limits used for structural design (from 9% and 39% to 19.5% and 46.5% mean aerodynamic chord). However, since the horizontal tail area for the Initial ACT Configuration was reduced by 45%, tail structural loading per unit area was increased.

The objective of the fuselage structural assessment for the Initial ACT Configuration was to provide guidelines for incremental weight estimates resulting from changes in fuselage design loads and to provide a basis for deriving aft body stiffnesses. The assessment reflected the reduced horizontal tail loads and the 1.68m (66-in) forward shift of the wing.

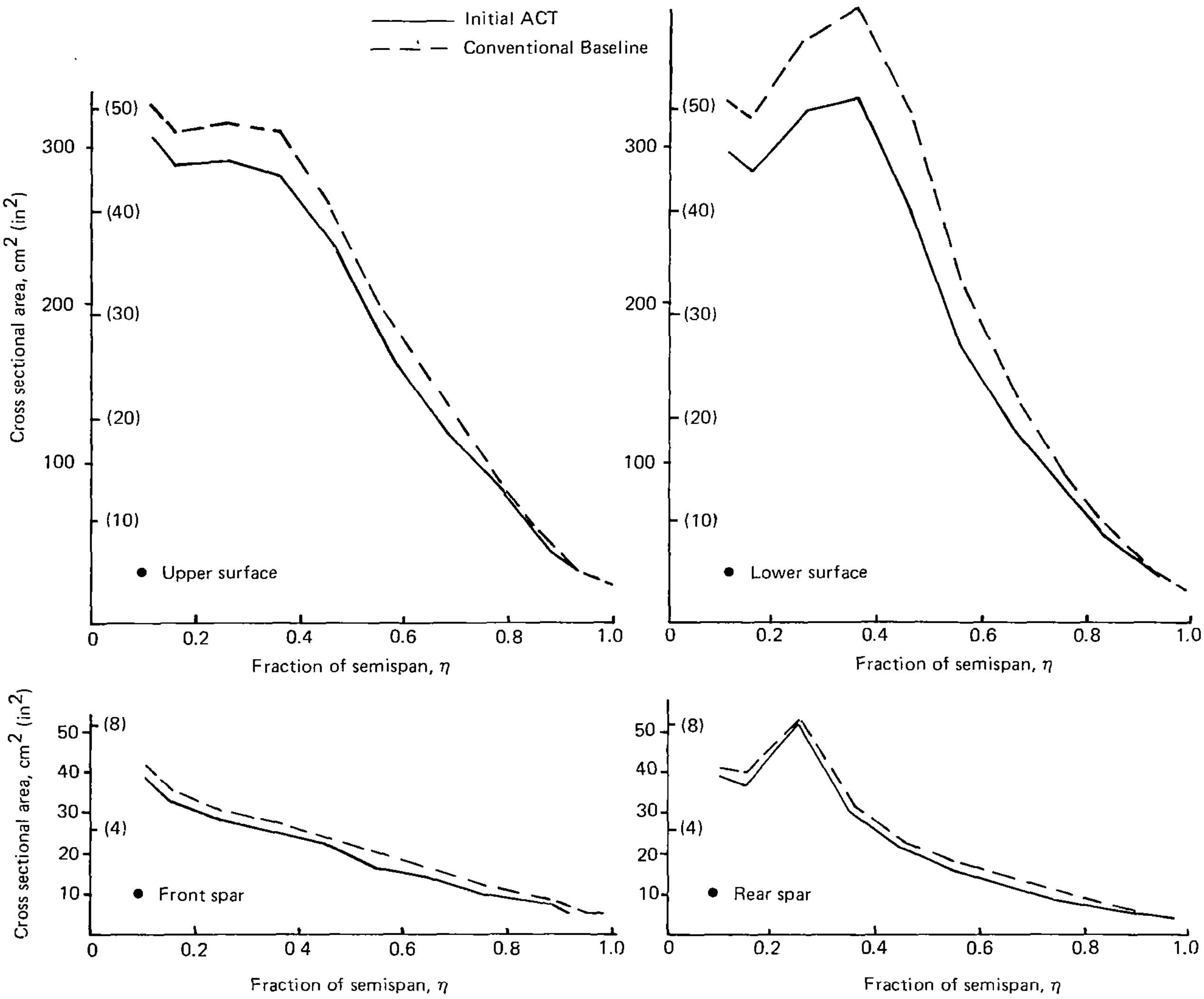


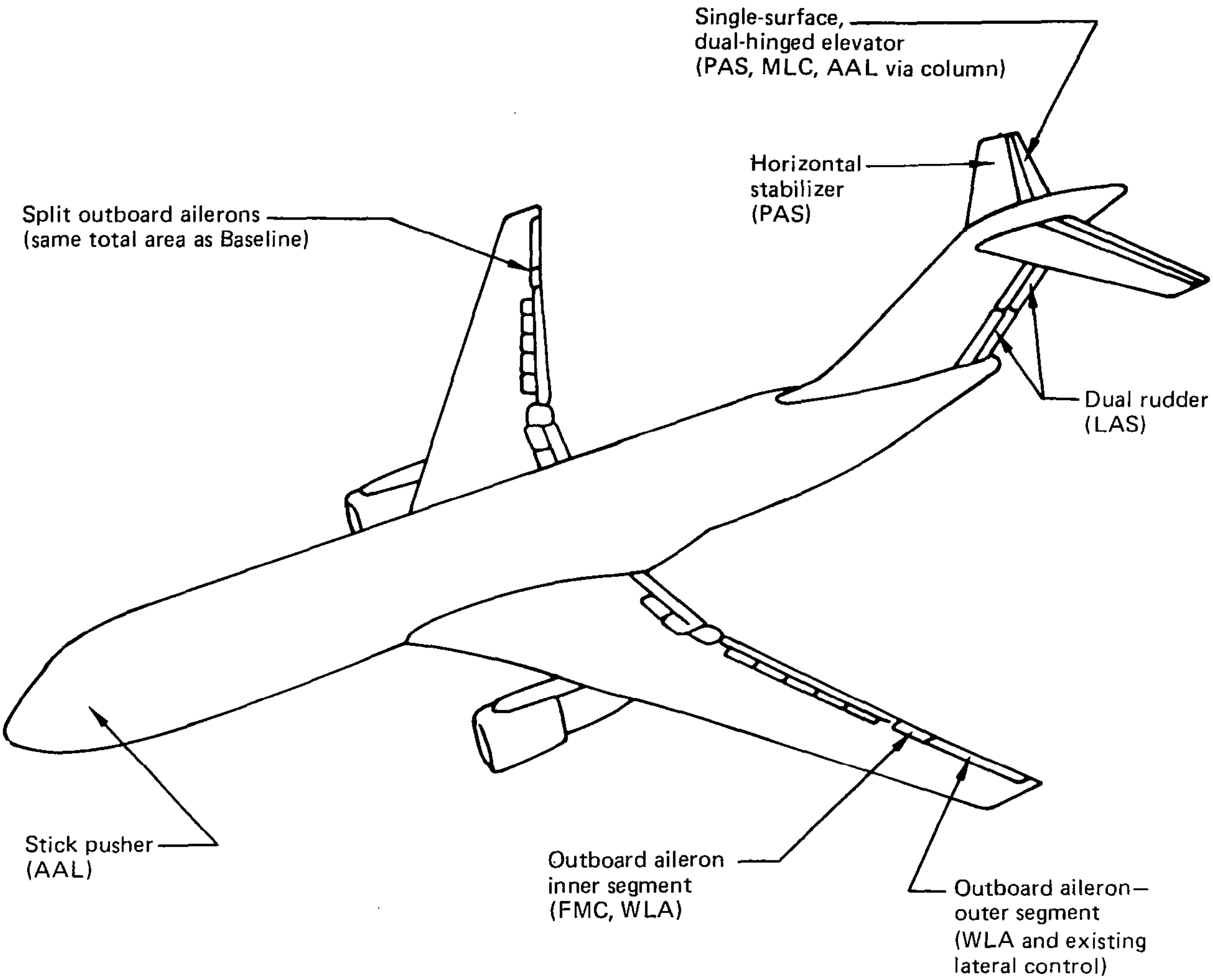
Figure 8. Final Wing-Box Structural Material Requirements

INITIAL ACT CONFIGURATION CONTROL SURFACES

The various ACT function control surface assignments are shown in Figure 9. The pitch-augmented stability (PAS) system is implemented through appropriate commands to the horizontal stabilizer and the dual-hinged elevator. The angle-of-attack limiting system is implemented as a stick pusher on the control column, thus commanding elevator deflection.

The lateral/directional-augmented stability (LAS) system is a conventional yaw damper that commands the dual double-hinged rudder, as on the Conventional Baseline Configuration.

The wing-load alleviation (WLA) system commands the outboard aileron (inner and outer segments) and the elevator (MLC). The flutter-mode control (FMC) system commands only the inboard segment of the outboard aileron.



ACT function	Control
PAS (short period)	Elevator
PAS (speed)	Elevator and stabilizer
LAS	Rudder
AAL	Column/elevator

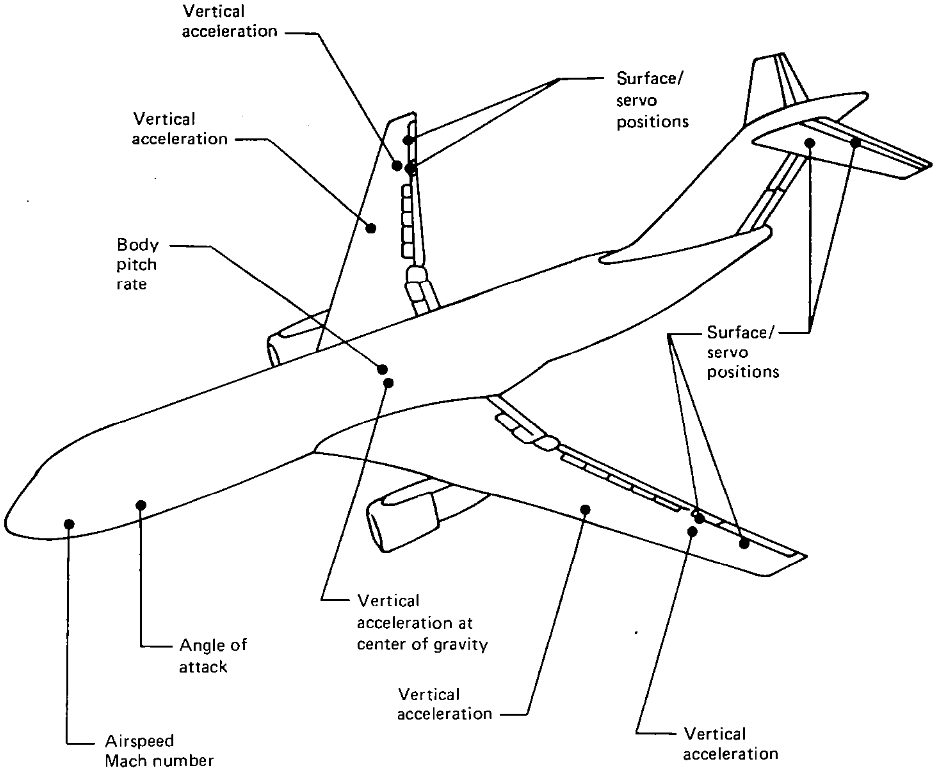
<table>
<tr><th colspan="2">ACT function</th><th>Control</th></tr>
<tr><td rowspan="2">WLA</td><td>MLC</td><td>Outboard aileron
Elevator (through PAS command)</td></tr>
<tr><td>GLA</td><td>Outboard aileron</td></tr>
<tr><td colspan="2">FMC</td><td>Outboard aileron (inner segment)</td></tr>
</table>

Figure 9. Control System Surfaces

ACT SYSTEM SENSORS

The active control system uses both shared and dedicated sensors to implement the various ACT functions. Figure 10 illustrates the general location of the major ACT sensors and their relationship to the ACT functions. Many of the sensor parameters required for ACT are already in the Baseline Configuration inertial reference system (IRS) and the digital air data computer (DADC), both configured in triplex. These computers provide airspeed, Mach number, angle of attack, pitch rate, and vertical acceleration at the center of gravity.

The dedicated pitch rate sensor, used in conjunction with the Baseline airplane triplex IRS pitch rate signal, is used to implement the quadruple PAS function. The remaining dedicated sensors; i.e., vertical acceleration at several wing locations, are generally simple triplex packages. Sensors are dedicated to their respective digital ACT computers, where data are then cross-channel transmitted to satisfy the redundancy requirements.



ACT Sensors

Initial ACT variable sensors	ACT functions					
	PAS		MLC	GLA	FMC	AAL
	Short	Long				
Pitch rate, body	X					X
Vertical acceleration at center of gravity			X			
Wing vertical acceleration–two locations				X	X	
Mach number					X	X
Airspeed		X	X	X	X	X
Angle of attack						X
Elevator secondary servo position	X	X	X			
Stabilizer position		X				
Outboard aileron, inboard segment position			X	X	X	
Outboard aileron, outboard segment secondary servo position			X	X		

Figure 10. ACT System Sensors

ACTIVE CONTROL SYSTEM MECHANIZATION

The Initial ACT Configuration active control system includes four ACT functions (PAS, WLA, FMC, and AAL). Figure 11 outlines the interface between major sensors, computers, and actuation systems. This ACT system shares sensors with the Baseline Configuration automatic flight control and avionic systems. Each computer receives signals directly from the sensors in the same channel, and data from the sensors in other channels are transferred from the other computers over cross-channel links. This cross-channel data communication scheme is also used for the automatic flight control system and other applications. The crucial ACT function PAS-short-period is mechanized with quadruple redundancy, and the critical functions (PAS-long-period, WLA, FMC, and AAL) are mechanized with triple redundancy. The critical functions are distributed among the four computers to minimize the probability of loss of all critical functions as a result of two computer failures. The four computers have identical software for interchangeability.

All input signals (analog, digital, and discrete) are consolidated in each computer signal selection and failure detection (SSFD) process. The SSFD provides an identical sensor signal to each computer for control law computation. Because the various ACT functions require different redundancy levels, depending upon functional criticality and failure conditions, the SSFD process is varied as necessary to handle the different types of sensor signals. The computers of the integrated system are frame synchronized; i.e., the same computations are executed at the same time in each computer. Using the SSFD and frame synchronization, the four computers produce identical command signals to the ACT actuators, which reduces the need for actuator equalization and simplifies the design. The identical command signal from each computer also simplifies the passive-failure, failure-detection algorithm. The redundant ACT command signals are consolidated at the actuator to provide a mechanical voting function. Two basic concepts are used in the ACT actuator design. For the control surfaces driven by the pilot's mechanical signal as well as ACT signals, a force-summed multiple-channel actuation system is used to convert the ACT electrical signals into a mechanical signal that series-sums with the pilot mechanical input. For the dedicated ACT control surfaces, the signal is fed directly to the ACT power control unit.

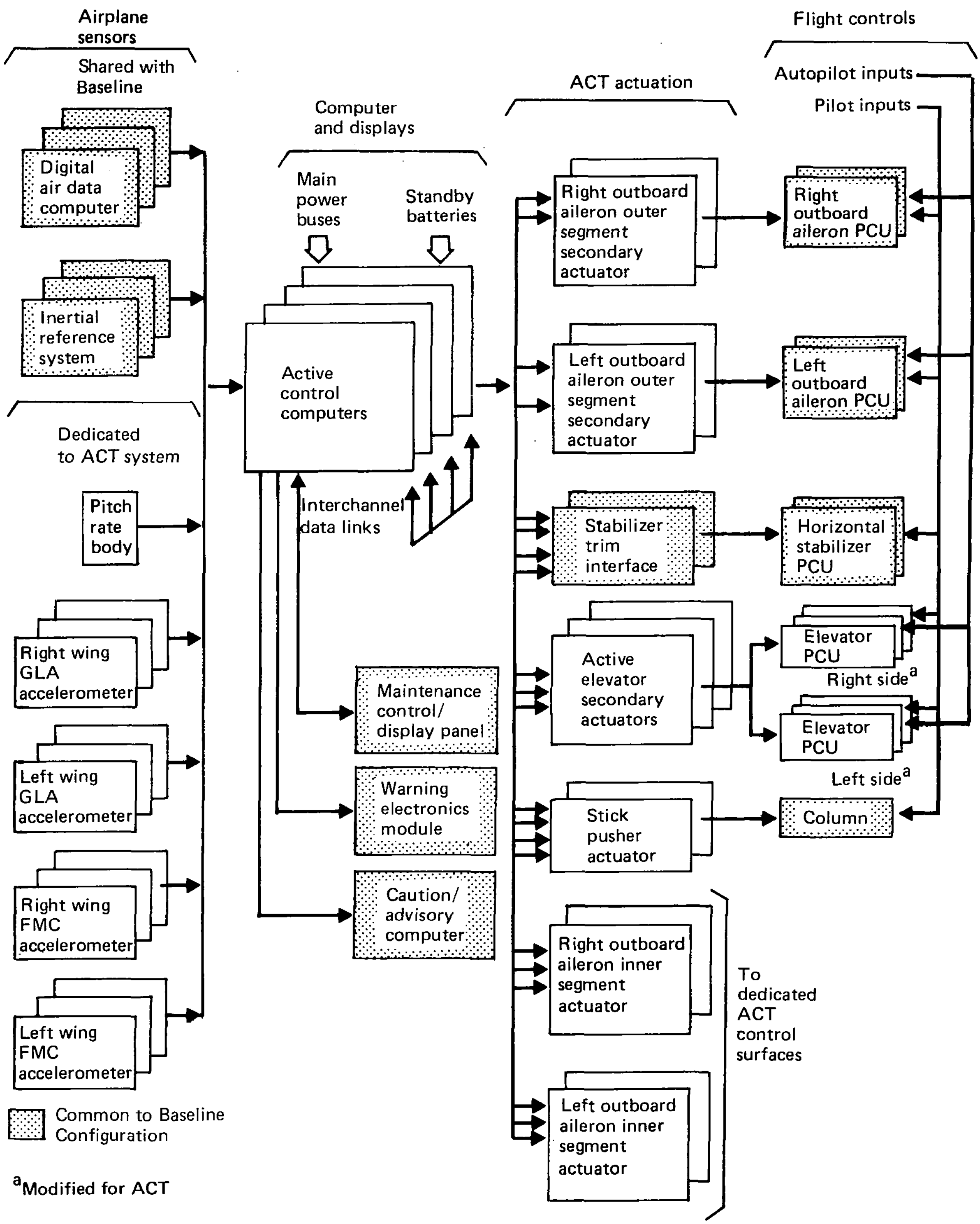


Figure 11. Initial ACT System Architecture

RELIABILITY AND MAINTAINABILITY

Reliability

The crucial ACT system PAS-short-period was designed to meet Federal Aviation Administration (FAA) requirements that the probability of loss of any function, which can result in aircraft loss, must be shown to be extremely improbable. FAA draft Advisory Circular, "Airplane System Design Analysis", advises that the term "extremely improbable" should be regarded as less than 1×10^{-9} failures per flight hour. This same circular also establishes an upper limit of 1×10^{-3} failures per flight hour for functional failures that require imposition of operational limitations. The latter limit was used as guidance concerning the allowable frequency of critical function failures that require flight envelope restrictions, provided that the failure rate did not exceed the failure rates for similar functions, which past experience has shown to be acceptable to the airlines. It is noteworthy that the major airlines, which provide data to Boeing on flight schedule deviation due to mechanical flight failure, do not consider flight envelope restriction as a flight schedule deviation, provided the airplane departs on time on the subsequent flight.

Analysis shows that when extremely improbable failure criteria must be met, a minimum of four channels are required; but where safe retreat into a restricted flight envelope is possible, three or less channels are sufficient. In the latter case, the redundancy should be selected based on cost-of-ownership analysis, which trades the first cost and maintenance cost of additional redundant channels for the ability to dispatch with certain components inoperative. However, because the crucial PAS system required four channels in the integrated Initial ACT system, such trades were not considered necessary at this stage of design.

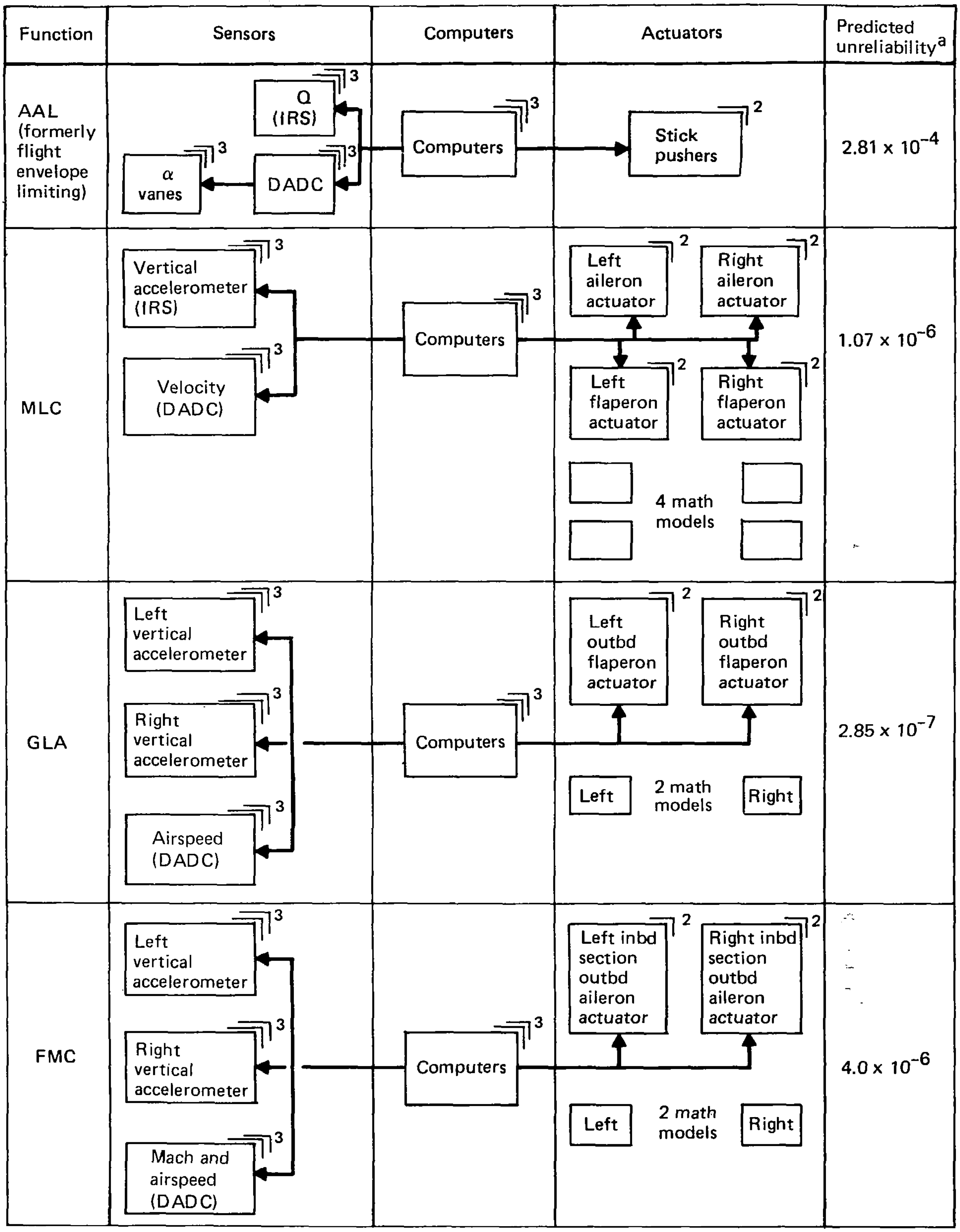
Based on the assumption that the very simple crucial PAS function software has a reliability of 1.0, the probability of total loss of the crucial PAS function was predicted to be 3.46×10^{-10}; i.e., less than the 1×10^{-9} failures per flight hour requirement of the FAA draft Advisory Circular. The component redundancy levels and predicted probabilities of complete loss of the critical ACT functions are shown in Figure 12.

Maintainability

The DRO maintainability requirements and objectives of particular importance to ACT are:

- At least 95% of the failures shall be successfully isolated to the LRU.
- Incorrect installation shall be impossible, particularly in crucial PAS.
- Automatic testing shall be used to minimize the need for scheduled maintenance.
- Components that can affect dispatchability shall be replaceable in a time that is compatible with the schedule reliability requirements.

Achievement of these objectives will greatly improve maintainability since only about 40% of current autopilot LRU removals are ever verified in the workshop.



[a]Assumes software reliability of 1.0

Figure 12. Probability of Total Loss of Critical ACT Functions

FUNCTIONAL WEIGHT ASSESSMENT

The functional weight assessment shown in Table 1 provides visibility of the increments constituting the net benefit of active controls. The table presents weight increments sequentially for the active control functions and systems as they were incorporated on the Initial ACT Configuration. This sequence was followed for the structural loads and sizing analysis. A deviation from this sequence would result in differences in functional weight increments attributed to each ACT function and accumulative OEW increments but would not alter the totals.

Note that the largest weight benefit of ACT for this configuration is due to the changes made possible through incorporation of relaxed static stability and angle-of-attack limiting.

Table 1. Weight Assessment of Active Controls

Active control function/system	OEW increment from Baseline Configuration		Cumulative subtotal OEW increment[a]	
	kg	lb	kg	lb
Relaxed static stability (RSS)	-414	-913	-414	-913
Move center-of-gravity aft limit aft from 38% MAC to 46% MAC. Included in the data are the effects of shifting the wing 1.68m (66 in) forward on the body:				
Reduce body primary structure due to reduced horizontal tail loads	-122	-270		
Reduce wing-box primary structure due to reduced horizontal tail loads	-73	-160		
Move main landing gear aft from 56% MAC to 64.9% MAC (reduced design loads)	-77	-170		
Change main landing gear design concept from conventional to swinging arm:				
Landing gear structure	+281	+620		
Body structure and cargo handling system	+195	+430		
Reduce horizontal tail area from 57.6 to 32.0 m^2 (620 to 344 ft^2); substitute double-hinged versus single-hinged elevator	-482	-1063		
Reduce vertical tail area from 57.4 to 54.0 m^2 (618 to 581 ft^2)	-257	-566		
Add pitch-augmentation system	+121	+266		
Add angle-of-attack limiter (AAL)	b	b		
Wing-load alleviation (WLA)	-659	-1452	-1073	-2365
Reduce wing-box primary structure due to reduced gust and maneuver loads	-780	-1720		
Add systems components: accelerometers, computer changes, and electric wiring	+122	+268		
Flutter-mode control (FMC)	+143	+315	-930	-2050
Reduce wing-box structure for FMC off flutter speed = V_D	-82	-180		
Segment outboard aileron	+64	+140		
Add flutter suppression system components (provide flutter speed capability = $1.2V_D$)	+25	+55		
Add one spoiler panel per side (five versus four)	+32	+70		
Add outboard structural reserve fuel tank	+104	+230		

[a]Subtotals are applicable only for the active control functional sequence shown.

[b]Stick pusher [24 kg or (53 lb)] was included in the weight definition of the Baseline Configuration. Normally, this feature is added with the RSS function.

CENTER-OF-GRAVITY MANAGEMENT

The center-of-gravity management (loadability) diagram is shown in Figure 13. The center-of-gravity loading range requirements include a tolerance (+3% MAC/-4% MAC) applied to the nominal operational empty weight (OEW) center of gravity to account for manufacturing variations and airline options such as increased cargo accommodations and engine substitution. The aft payload envelope is critical for 197 mixed-class passengers (18 first class and 179 tourist class) and establishes the aft center-of-gravity envelope for payload. The forward envelope is critical for 207 tourist passengers and establishes the forward center-of-gravity envelope for payload.

The forward and aft cargo compartment cargo moment vectors are based on 22 LD-2 containers at 105-kg/m^3 (6.58-lb/ft^3) density. Adding vectors for the bulk cargo compartment completes the loading envelope for the zero fuel weight airplane. Maximum design zero fuel weight (MZFW) establishes the maximum allowable payload.

The fuel system includes one main tank and one structural reserve tank per side. The structural reserve tanks, incorporated into the outboard wing for flutter stability, have a capacity of 1406 kg (3100 lb) per airplane. Normal operational speeds and speed margins are available only with this tank full. Transfer of fuel from the structural reserve tank would normally occur when the total airplane fuel is 3180 kg (7000 lb) or less, in combination with a reduction in operational and limit speeds to retain appropriate speed margins.

The forward and aft required flight center-of-gravity limits must allow the loading of full containerized cargo, with or without bulk, with any passenger load (assuming seating order is window, aisle, then remaining seats). The aft operating limit is established forward of the aft flight limit by a moment margin that covers in-flight movements of passengers and crew, control surface deflections, landing gear movements, and fuel vector moment difference. The forward operating limit is established by the center-of-gravity range required for payload and fuel loadability. The 21% MAC forward required flight limit, then, clears the forward operating limit by a similar margin for in-flight movement and fuel moment difference (footnote a, fig. 13).

The typical cruise center of gravity is based on a payload definition consistent with the performance analysis ground rules used for a typical airline customer.

For the Initial ACT Configuration, the 46% MAC aft required flight limit is slightly exceeded by the extreme aft loading distribution of passengers plus cargo payload. A ballast of 272 kg (600 lb) would be required in the nose-gear wheel well to stay within the design center-of-gravity envelope. However, a wing shift aft of approximately 0.051m (2 in) would eliminate this aft center-of-gravity problem with minor weight changes. Resources and time were not available to recycle the configuration. No ballast weight is included in the Initial ACT OEW, thus compatibility with the Conventional Baseline airplane and subsequent IAAC study configurations is maintained.

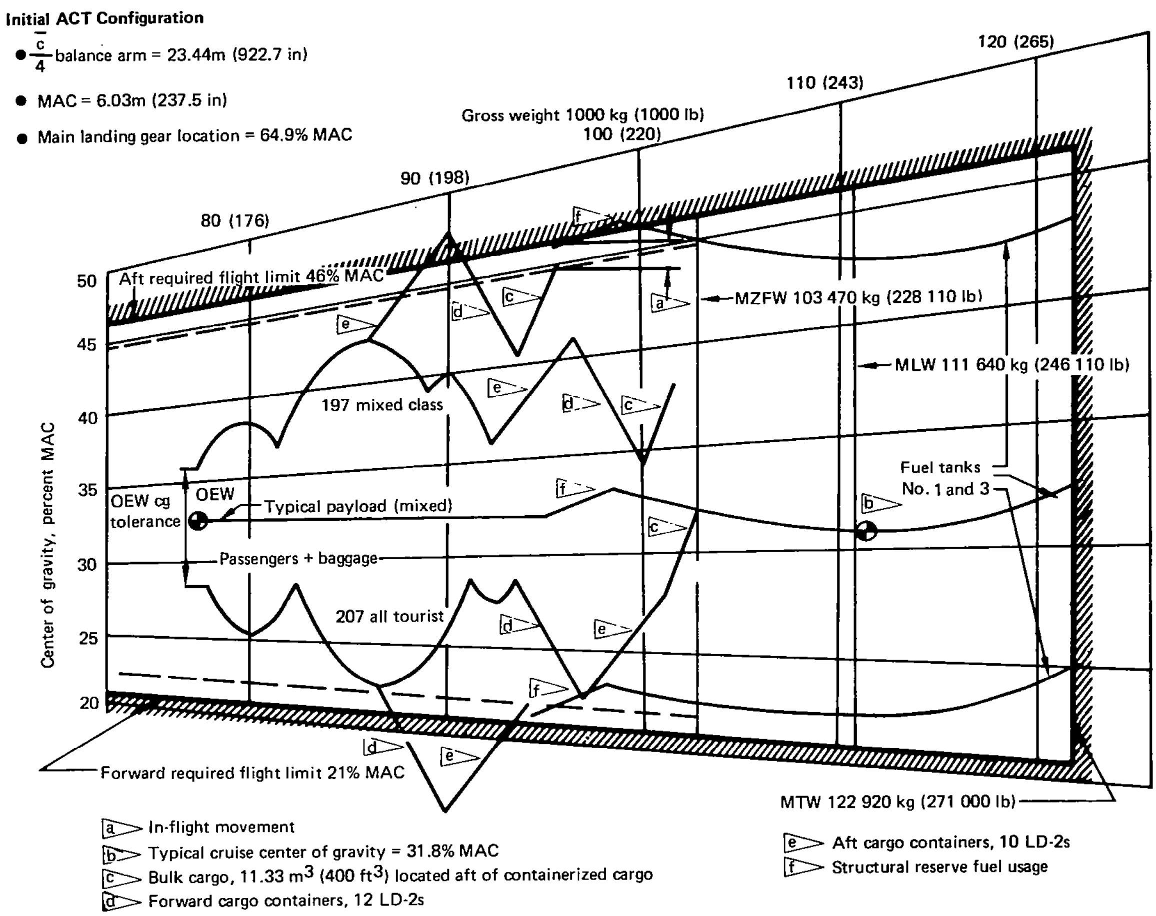


Figure 13. Center-of-Gravity Management

AERODYNAMICS

The Initial ACT Configuration exhibits lower drag, relative to the Baseline Configuration, due to reductions in trim and skin friction drag associated with the smaller horizontal tail, farther aft center of gravity, and longer tail arm resulting from the forward wing shift. The cruise lift-to-drag ratio (L/D) was improved 3.6% (table 2), and takeoff L/D was increased 2.3%. Both airplanes have the same gross weight, engine size, wing area, and payload.

The 2.3% improvement in takeoff L/D was mainly the result of the farther aft location of the forward center-of-gravity position for the Initial ACT Configuration. The high-lift systems of these two airplanes are identical and consist of single-slotted trailing-edge flaps and full-span leading-edge slats with both sealed and slotted positions. Takeoff speed schedules and times for the Initial ACT Configuration are unchanged from those of the Conventional Baseline Configuration.

The 3.6% drag improvement for the Initial ACT Configuration, at an average cruise condition (C_L = 0.45, Mach = 0.8), was due to reduced skin friction drag from a smaller tail size (2.4%) and reduced trim drag. The 1.2% trim drag reduction at cruise (C_L = 0.45) was due primarily to the farther aft cruise center-of-gravity position. Cruise drag polars for the Initial ACT and Baseline Configurations were based on wind tunnel test data of similar configurations, with empirical and analytical corrections for small geometric differences.

Table 2. Conventional Baseline and Initial ACT Configuration Performance Comparison

	Baseline		Initial ACT		Δ	
MTW, kg (lb)	122 920	(271 000)	122 920	(271 000)	---	
TOGW, kg (lb)	122 470	(270 000)	122 470	(270 000)	---	
ZFW, kg (lb)	104 400	(230 160)	103 470	(228 110)	-930	(-2050)
MLW, kg (lb)	112 560	(248 160)	111 640	(246 110)	-930	(-2050)
OEW, kg (lb)	78 300	(172 610)	77 370	(170 560)	-930	(-2050)
Forward cg, percent MAC	10.0		21.0		+11.0	
Average cruise cg, percent MAC	20.5		31.8			(+11.3)
Cruise L/D, (M = 0.8, C_L = 0.45)	Base		(+3.6)			(+3.6)
SAR, km (nmi)	3 589	(1 938)	4 061	(2 193)	+472	(+255)
TOFL, SL, 29°C (84°F) m (ft)	2 210	(7 250)	2 118	(6 950)	- 92	(-300)
V_{APP} at maximum landing weight, m/s (kn)	70.0	(136.1)	68.6	(133.4)	-1.4	(-2.7)
Landing field length, sea level, dry, at maximum landing weight, m (ft)	1 443	(4 735)	1 402	(4 600)	-41	(-135)

PERFORMANCE

Performance improvements for the Initial ACT Configuration compared to the Baseline Configuration are shown in Table 2. The improved still air cruise range resulted from reduced drag and reduced operating empty weight (OEW). The drag improvement increased the range about 204 km (110 nmi). This includes the benefit of increased midcruise step weight; i.e., because of the increased L/D, the 1219m (4000-ft) step in cruise altitude is made earlier at a higher weight. The reduced OEW and reserve fuel added 269 km (145 nmi), for a total improvement of approximately 13% or 472-km (255-nmi) still air range (SAR).

The takeoff performance improvement of the Initial ACT Configuration was due primarily to reduced trim drag from a farther aft forward-center-of-gravity limit (10% to 21% MAC) and longer tail arm. The overall takeoff field length (TOFL) improvement was 91.4m (300 ft) at sea level, 29°C (84°F) at maximum takeoff gross weight (TOGW) conditions, and includes the geometry limit condition. Approach speed of the Initial ACT Configuration is somewhat reduced, 1.4 m/s (2.7 kn), with a reduced tail clearance angle at touchdown of about 1 deg.

The net fuel savings versus mission still air range are shown in Figure 14. At the average mission stage length, 863 km (466 nmi), the Initial ACT Configuration requires 3.3% less block fuel. At the Baseline range limit, 3589 km (1938 nmi), the Initial ACT Configuration exhibits a 6% reduction in block fuel. For a fixed design TOGW of 122 470 kg (270 000 lb), the reduced drag (9.2 counts) and OEW of 930 kg (2050 lb) increased the still air range by 472 km (255 nmi).

In summary, relative to the Conventional Baseline Configuration, the Initial ACT Configuration exhibits significant performance benefits for an airplane with the same gross weight, payload, engine, and wing size.

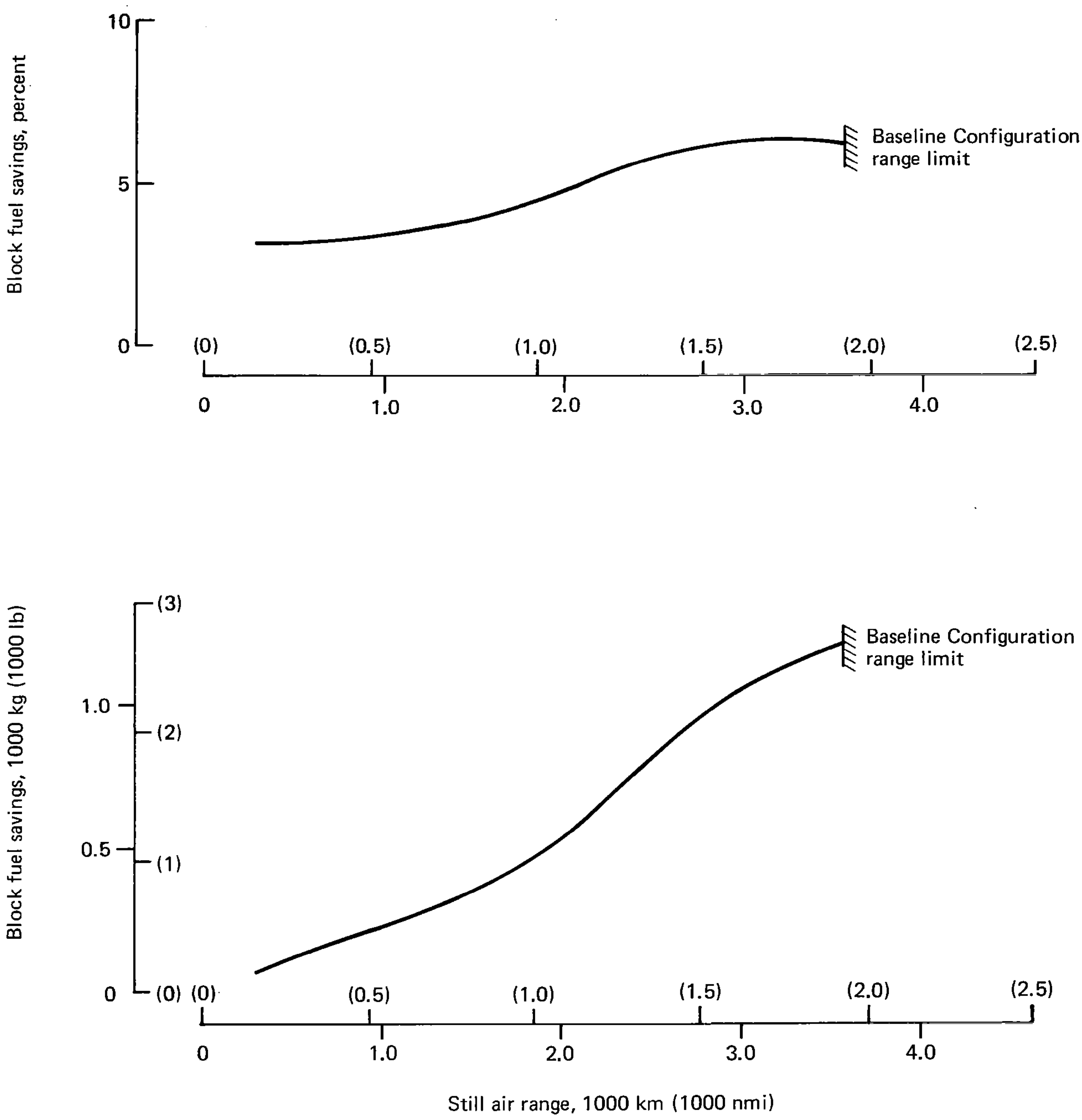


Figure 14. Block Fuel Savings

RETURN ON INVESTMENT

Return on investment (ROI) for the airplane operator is a more complete measure of the benefit associated with ACT than is airplane performance alone. Incremental ROI was selected as an appropriate economic metric for an ACT airplane, as ACT is being examined as an alternative to conventional design. The ROI estimate for the Initial ACT Configuration is based on a 300-airplane buy and the following incremental ACT effects based on 1978 dollars and fuel cost:

- $300,000 per aircraft incremental cost of adding ACT to the Baseline design (includes recurring and nonrecurring costs).
- Fuel savings of 160 kg (352 lb) per flight hour at average operating range of 863 km (466 nmi).
- Additional maintenance and delay and cancellation costs of $5.34 per flight hour.
- Additional maintenance manual cost of $21,000 per 30-airplane fleet.
- Incremental test equipment cost of $22,500 per 30-airplane fleet.
- Additional training expense for ACT was judged to be negligible (training costs are included in airplane price).

The minimum attractive ROI for an airline was judged to be 15%. The resulting incremental ROI was 15.73%, or almost three-quarters of a percent above the assumed 15% minimum.

Figure 15 illustrates the impact of changes in several cost-of-ownership parameters on this potential margin. It is encouraging to note that the incremental ROI is relatively insensitive to changes in maintenance and delay cost and very sensitive to changes in fuel cost or savings. This sensitivity to fuel price will become even more important if fuel price yearly inflation rates follow historical trends and exceed wholesale price indices and maintenance cost inflation rates, as the current ROI model assumes equal inflation rates for all airplane direct operating cost elements.

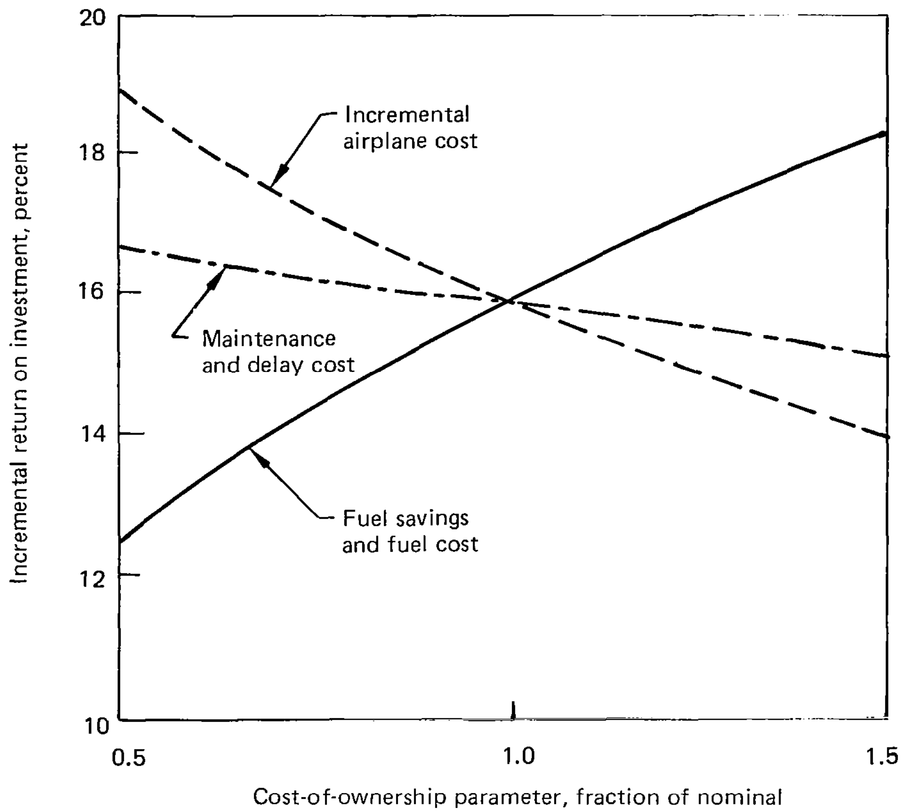


Figure 15. Effect of Changes in Cost Parameters on Incremental Return on Investment

CONCLUSIONS

The configuration design and evaluation activities of the IAAC Project focused on configurations suitable for medium-range missions as such missions constitute a major share of domestic airline operations and, thereby, high total fuel usage. Specifically, the Conventional Baseline Configuration was designed to a 197-passenger, nominal 3590-km (1938-nmi) design range mission requirement. A two-engine, seven-abreast seating configuration was selected for the Baseline because a large analytical and wind tunnel test data base was available. The DRO for that configuration was evaluated and modified as appropriate to take into account the expected impact of ACT.

The outline geometry of the Conventional Baseline Configuration and the Initial ACT Configuration (cross-hatched) are shown in Figure 16. The Initial ACT Configuration was constrained by the following ground rules:

- Takeoff gross weight, propulsion system, wing planform area and spar locations, and empennage planform remained the same as the Baseline Configuration.
- All beneficial ACT functions were assumed available.
- Operational and passenger/cargo flexibility of the Baseline Configuration was retained.
- Wing movement, relative to the Baseline Configuration, was a multiple of standard cargo containers.

The IAAC Project has shown that active controls can provide a significant performance improvement, with associated fuel savings, at a predicted reasonable incremental ROI. This improvement is a 13% increase in range (at constant gross weight) or a 6% reduction in block fuel (at the Baseline range limit) for the Initial ACT Configuration relative to the Baseline.

Based on analyses accomplished to date, the required ACT control systems appear feasible with current control system technology, certification rules, and procedures, although considerable work remains to be done. In order for ACT to become an integral part of future commercial transports, control system development (including acquisition, laboratory test, and, potentially, flight test) of critical ACT system elements must proceed. These activities should address concerns with hardware and software implementation of the ACT functions and flying qualities characteristics with normal and failed ACT systems under various weather conditions.

The predicted incremental ROI (based on factored cost data) for the Initial ACT Configuration is in excess of 15%, even at 1978 fuel prices and dollars. Considerably greater ROI benefits will result if historical fuel inflation rates persist. Assuming the resized Final ACT Configuration exhibits further performance improvement and the ACT systems implementation remains feasible, the final incremental ROI should be even better.

<table>
<tr><th></th><th>Baseline Configuration</th><th>Initial ACT Configuration</th></tr>
<tr><td>Passengers
Mixed class
All tourist</td><td colspan="2">
197
207</td></tr>
<tr><td>Containers,
LD-2 or LD-3</td><td colspan="2">22 or 11</td></tr>
<tr><td>Engines</td><td colspan="2">(2) CF6-6D2</td></tr>
<tr><td>Wing area, m^2 (ft^2)</td><td colspan="2">256.3[a]
(2759)</td></tr>
<tr><td>Maximum takeoff gross weight, kg (lb)</td><td colspan="2">122 470
(270 000)</td></tr>
<tr><td>Operating empty weight, kg (lb)</td><td>78 300
(172 610)</td><td>77 370
(170 560)</td></tr>
<tr><td>Design range, km (nmi)</td><td>3590
(1938)</td><td>4061
(2193)</td></tr>
<tr><td>Takeoff field length, m (ft)</td><td>2210
(7250)</td><td>2118
(6950)</td></tr>
<tr><td>Cruise Mach</td><td colspan="2">0.8</td></tr>
</table>

[a]Trapezoid geometry quoted, aero reference area—275.1 m^2 (2961 ft^2)

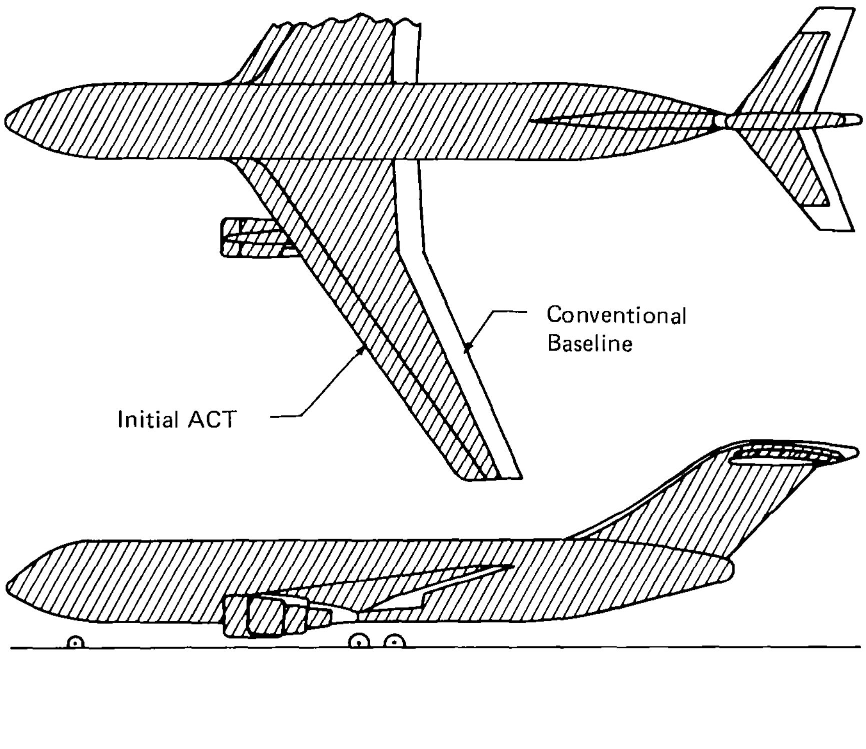


Figure 16. Conventional Baseline Configuration and Initial ACT Configuration Comparison

REFERENCES

1. Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Initial ACT Configuration Design Study, Final Report, NASA CR-159249, 1980.

2. Program Plan for Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport, NASA CR-3305, 1980.

3. Fuel Cost and Consumption, Summary Report, Civil Aeronautics Board, CAB 1.15-1978.

4. Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Conventional Baseline Configuration Study, NASA CR-159248, 1980.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-3304		

4. Title and Subtitle	5. Report Date
Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project — Initial ACT Configuration Design Study, Summary Report	October 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Staff of Boeing Commercial Airplane Company (Preliminary Design Department)	D6-48671
	10. Work Unit No.
9. Performing Organization Name and Address	
Boeing Commercial Airplane Company P. O. Box 3707 Seattle, Washington 98124	11. Contract or Grant No. NAS1-14742 & NAS1-15325
	13. Type of Report and Period Covered Contractor Report August 1978 to September 1979
12. Sponsoring Agency Name and Address	
National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Langley Technical Monitors: David B. Middleton and Ray V. Hood, Jr.

Summary Report for NASA CR-159249.

16. Abstract

This report summarizes the Initial ACT Configuration Design Task of the Integrated Application of Active Controls (IAAC) Technology Project within the Energy Efficient Transport Program. A constrained application of Active Controls Technology (ACT) resulted in significant improvements over a Conventional Baseline Configuration (Baseline) previously established. The configuration uses the same levels of technology, takeoff gross weight, payload, and design requirements/objectives as the Baseline, except for flying qualities, flutter, and ACT. The Baseline wing is moved forward 1.68m. The configuration incorporates pitch-augmented stability (which enabled an approximately 10% aft shift in cruise center of gravity and a 45% reduction in horizontal tail size), lateral/directional-augmented stability, an angle-of-attack limiter, wing-load alleviation, and flutter-mode control. This resulted in a 930-kg reduction in airplane operating empty weight and a 3.6% improvement in cruise efficiency, yielding a 13% range increase. Adjusted to the 3590-km Baseline mission range, this amounts to 6% block-fuel reduction and a 15.7% higher incremental return on investment, using 1978 dollars and fuel cost. Results of the Initial ACT Task indicate that the IAAC Project should proceed to determine further benefits achievable through wing planform changes and advanced technology systems.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Energy Efficient Transport Program, Active Controls Technology, Augmented Stability, Wing-Load Alleviation, Flutter-Mode Control Angle-of-Attack Limiter, Airplane Design	FEDD Distribution Subject Category 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	41	

Available: NASA's Industrial Applications Centers

NASA-Langley, 1980